UDC 621.396.66
621.391.812.31

BBC

RESEARCH DEPARTMENT

1969
THE QUEEN'S AWARD
TO INDUSTRY

REPORT

H. F. RADIO LINKS: the feasibility of an automatic equaliser for correcting amplitude/frequency response distortion

No. 1972/11

Research Department, Engineering Division
THE BRITISH BROADCASTING CORPORATION

RESEARCH DEPARTMENT

H.F. RADIO LINKS: THE FEASIBILITY OF AN AUTOMATIC EQUALISER FOR CORRECTING AMPLITUDE/FREQUENCY RESPONSE DISTORTION

Research Department Report No. 1972/11
UDC 621.396.66
621.391.812.31

It uses SI units in accordance with B.S. document PD 5686.

N.H.C. Gilchrist, B.Sc.

Head of Research Department

(EL-62)

Research Department Report No. 1972/11

H.F. RADIO LINKS: THE FEASIBILITY OF AN AUTOMATIC EQUALISER FOR CORRECTING AMPLITUDE/FREQUENCY RESPONSE DISTORTION

(EL-62)

May 1972

Research Department Report No. 1972/11
UDC 621.396.66
621.391.812.31

H.F. RADIO LINKS: THE FEASIBILITY OF AN AUTOMATIC EQUALISER FOR CORRECTING AMPLITUDE/FREQUENCY RESPONSE DISTORTION

Summary

The fading which occurs on long-distance h.f. broadcast links frequently causes distortion of the amplitude/frequency response of the link to the modulating signal. A type of equaliser is described for providing continuous correction of the audio response, involving the use of a number of pilot tones which are added to the programme before transmission.

The results of tests on a first experimental model showed the inadequacy of applying correction in four audio bands, when dealing with a typical h.f. path. Inferences drawn from the tests suggest that either a more elaborate version of the equaliser or a different approach is required.

1. Introduction

The more remote transmitters of the Overseas Service obtain their programme feed either by relaying standard h.f. broadcasts (double sideband) or via radio links operating in the h.f. bands. These links normally employ single-sideband (s.s.b.) amplitude modulation, with a partially suppressed carrier-frequency component.

The transmitted waves reach the link receiver via a number of paths, usually involving two or three ionospheric reflections.[1] Differences between the lengths of the paths involved cause differential time delays of the order of 2 ms. As a result of interference between the waves at the receiver, with the path lengths continually changing owing to irregularities in the ionosphere, the signal strength at the receiver changes between a maximum when all the waves arrive in phase and a minimum when cancellation occurs. It is clear that the relative phases of the waves arriving at the receiver depend on the frequency as well as the respective path lengths. Thus it is possible for components of the received sidebands at certain frequencies to be attenuated relative to other components, resulting in modification of the audio spectrum of the modulation. When fading is severe it is possible for deep minima to appear in the spectrum of the modulating signal. Frequency-selective fading of this type results in a particularly objectionable effect; the programme sounds as if it were originating from a tunnel or similar resonant enclosure.

The equaliser described in this report operates after demodulation and divides the a.f. spectrum into four bands. Pilot tones of equal amplitude, which are added to the programme before modulation, are examined by the equaliser, and control circuits then adjust the gain of the amplifier controlling each band so that the pilot tones are maintained at the same amplitude. Since the audio pilot tones must be removed by special filters at the receiver, this system cannot be applied to transmissions intended for direct reception by the public.

2. Theoretical description

2.1. The transmitting terminal

For the equaliser to be able to assess continuously the nature of the non-uniform response, pilot tones of constant amplitude are added to the programme material. It was decided to use three pilot tones, and to control the levels of three frequency bands in the spectrum of the programme. The spectrum was divided into four bands but no adjustment was made to the lowest frequency band, as it was assumed, for the purpose of preliminary investigations, that the receiver a.g.c. could satisfactorily stabilise the gain of the link at low frequencies. The pilot tone frequencies were 1·185 kHz, 2·37 kHz and 3·8 kHz (these being derived fairly readily by division from a 19 kHz crystal-controlled oscillator) so that the shape of the programme spectrum could be controlled by adjusting gain in the frequency bands 600 Hz – 1·8 kHz, 1·8 kHz – 3·0 kHz and 3·0 kHz – 5·5 kHz (as a nominal upper limit of the audio frequencies carried).

The general arrangement of the transmitting terminal is shown in the block schematic diagram of Fig. 1, and will be seen to comprise three cascaded notch (band-stop) filters, a summing amplifier, an oscillator and a divider. The notch

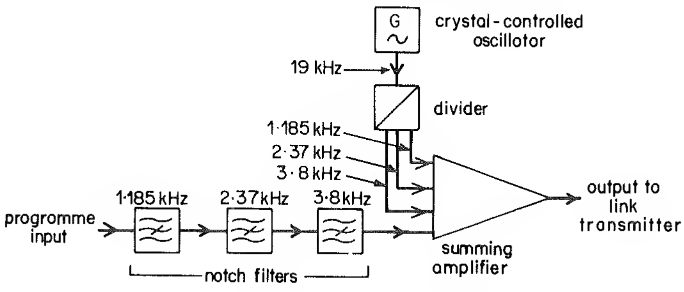

Fig. 1 - Block schematic diagram of the transmitting terminal

filters provide 'slots' in the spectrum for the pilot tones, and are needed to reduce the breakthrough of programme information into the control circuits at the receiving terminal; the pilot tones are provided by the 19 kHz divider, which is a binary counter with division by five, eight and sixteen. Filters are incorporated in the divider to ensure that the pilot tones are sinusoidal, as harmonics could interfere with the programme.

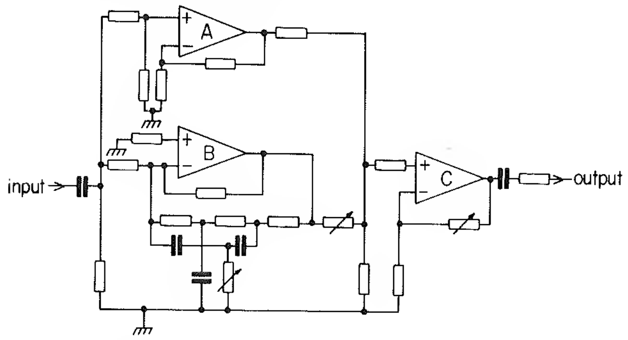

Fig. 2 - Circuit diagram of the active notch filter

In order to achieve the required quality factor Q, it proved necessary to use active circuits for the notch filters providing the tone slots. A circuit diagram for one of the filters is shown in Fig. 2. The parallel –T network in the feedback loop associated with the operational amplifier B determines the notch frequency, and fine tuning adjustments may be made by varying just two resistors in this circuit.[2] This combination acts as a selective filter with a narrow passband,[3] and its output is added to that of amplifier A via a preset resistive attenuator. Adjustment of the attenuator enables a deep notch to be obtained when the signals from the output of amplifier B just cancel those from amplifier A, as the two amplifier outputs are in antiphase at the stop frequency. A third amplifier (C) provides a measure of gain and a low output impedance as well as acting as a buffer stage to minimise the effect of output loading on filter performance.

The programme, with pilot tones added, modulates the link carrier in the usual way. For the experimental work, the pilot tones were set at a level of –20 dB relative to peak programme. At this level noise on the tones presents no problem, and they are not difficult to remove from the programme after equalisation.

2.2. The receiving terminal

A block schematic diagram of the receiving terminal is shown in Fig. 3, and its operation is as follows. Programme is fed from the link receiver into a set of band-separating filters which divide the spectrum of the signal into four separate frequency bands. The lowest band of frequencies passes directly to a summing amplifier whilst the other three components of the signal pass through gain-controlled amplifiers before reaching the summing amplifier. Pilot-tone levels are measured at the output of the summing amplifier by detectors operating in conjunction with high-Q active filters, and d.c. control voltages are applied to the controlled amplifiers in such a way as to correct discrepancies in the levels of the tone. Notch filters remove the pilot tones from the signal before it leaves the equaliser.

The amplitude/frequency response of a 2·37 kHz notch filter, which is used in the transmitting terminal as

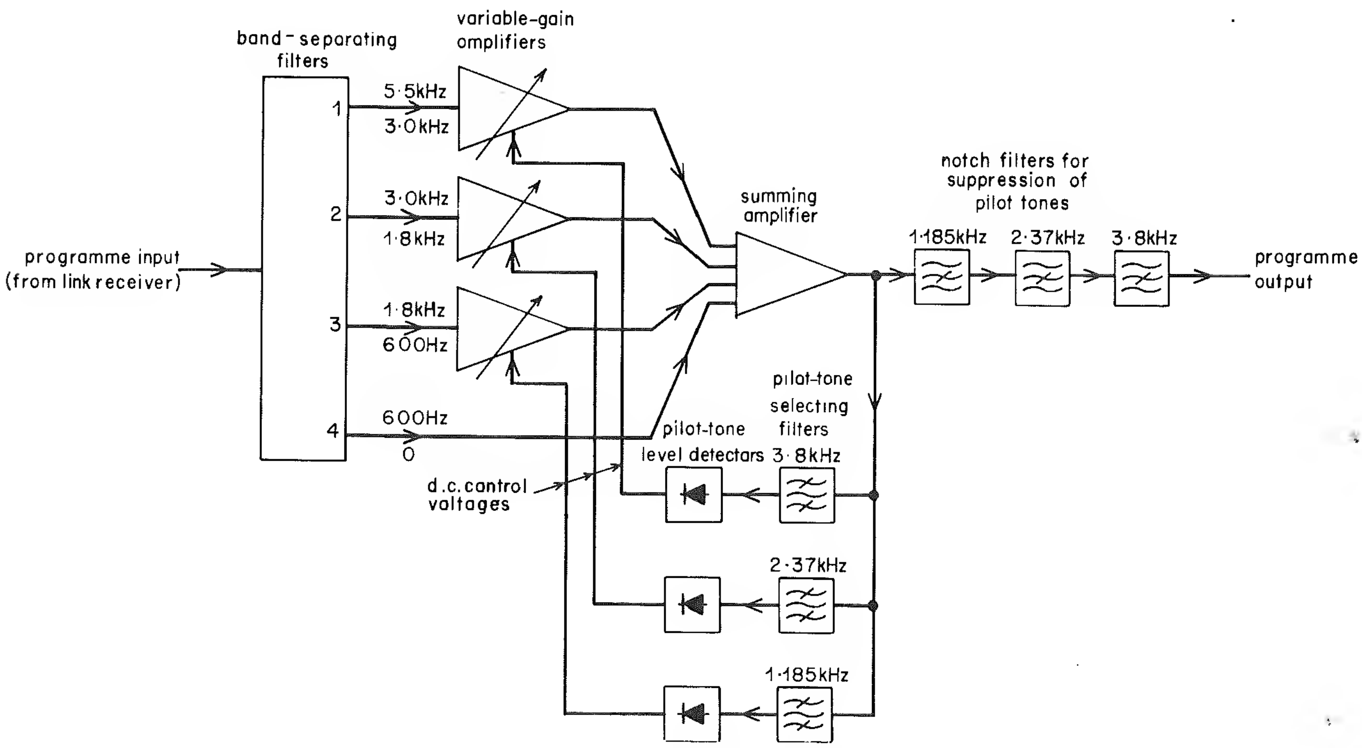

Fig. 3 - Block schematic diagram of the receiving terminal

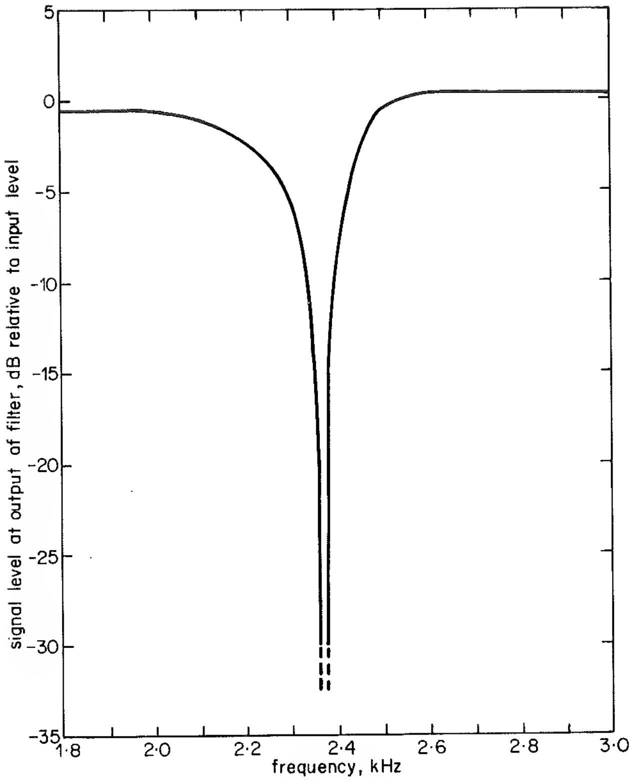

Fig. 4 - Frequency response of 2·37 kHz active notch filter

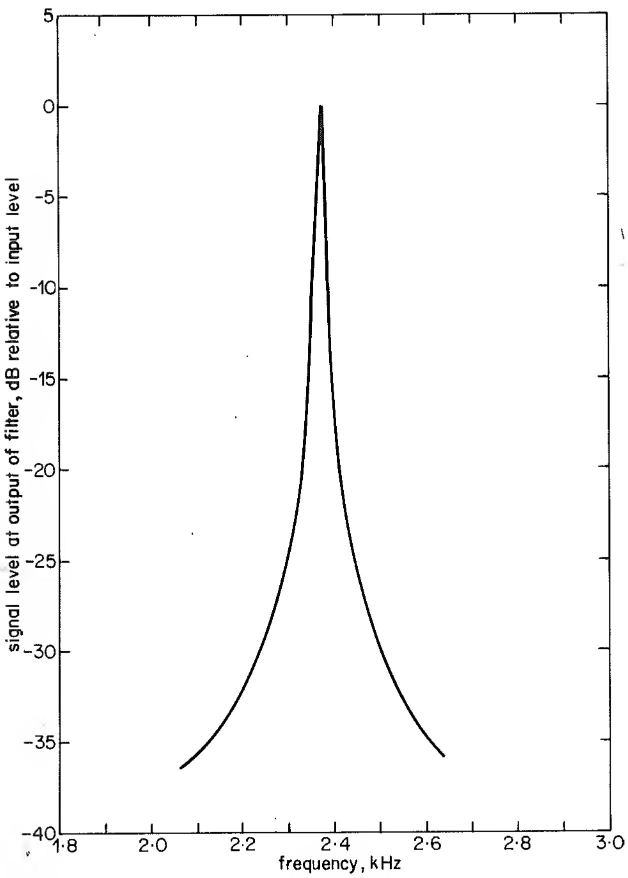

Fig. 5 - Frequency response of 2·37 kHz pilot tone selecting filter

well as the receiving terminal, is shown in Fig. 4. Responses are not shown for the other notch filters, but they have a similar performance. Fig. 5 shows the response of the 2·37 kHz pilot-tone selecting filter which is used to extract a pilot tone for control purposes. There are three such tone selecting filters; each is identical to the selective amplifier section of a notch filter. The circuit is that of Fig. 2, but with the omission of amplifier A.

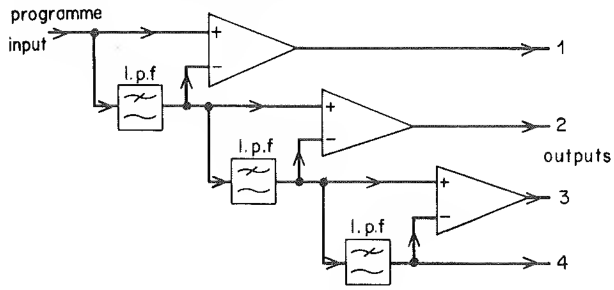

Fig. 6 - Block schematic diagram of band separating filters

The filters which are employed at the input of the receiving terminal to divide the programme into separate bands of frequencies consist of active low-pass filters operated in conjunction with difference amplifiers. A block schematic of the arrangement is presented in Fig. 6. The first low-pass filter has a cut-off frequency of 3·0 kHz and the output of this filter is subtracted from the total signal in the first difference amplifier. The output of the difference amplifier is thus equivalent to that of a high-pass filter with a cut-off frequency of 3·0 kHz. A second output from the low-pass filter feeds another difference amplifier and another low-pass filter with a cut-off frequency of 1·8 kHz arranged to give a high-pass filter characteristic (this time with a cut-off at 1·8 kHz). Thus an output is available within a pass band from 1·8 kHz to 3·0 kHz. A further low-pass filter and amplifier provide outputs of the programme spectrum in two bands: 600 Hz to 1·8 kHz and 0 to 600 Hz. Fig. 7 shows the frequency response curves for the filters. Output 2 is at a slightly lower level

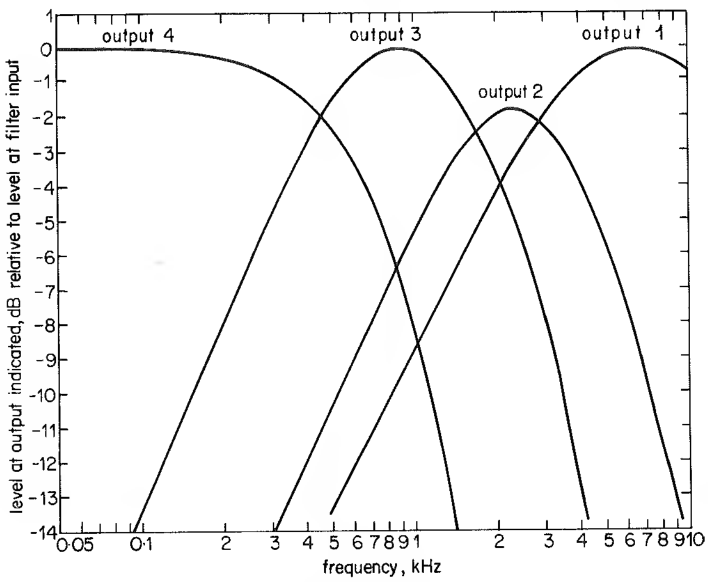

Fig. 7 - Frequency response of band separating filters measured at individual outputs

than the others; this is because there is a considerable overlap into the passband of output 2 from outputs 1 and 3.

This technique enables a set of bandpass filters to be constructed with complementary characteristics in the regions of the spectrum where they overlap. When the outputs are added together, there is a smooth transition from one band to the next, and the effectiveness of the technique is demonstrated by the graph of Fig. 8. The slight falling-off of the response at higher frequencies is of no consequence in this application, but could probably be eliminated by selecting the feedback resistors of the difference amplifiers to ensure equality of gain.

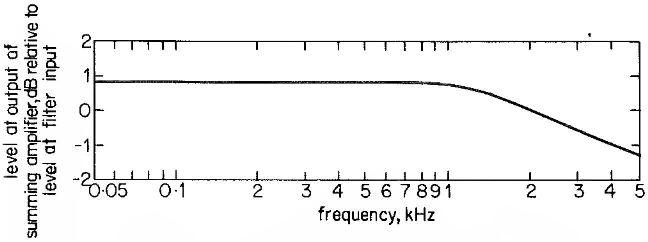

Fig. 8 - Frequency response of band separating filters with outputs combined by summing amplifier with unity gain

3. Experimental work

3.1. Objective tests

The transmitting and receiving terminals of the automatic equaliser were initially set up in adjacent positions with a direct connection between the two units, and the pilot-tone detectors set up to give the complete system a flat frequency response. Limits were set to the d.c. control voltages applied to the gain-controlled amplifiers, and these were arranged so that the range of gain adjustment available was restricted to ±20 dB. This restriction was considered necessary in order to reduce the severity of the disturbance which could be caused to the programme spectrum by a deep null occurring at the frequency of one of the pilot tones.

In order to test the effectiveness of the control circuits in the receiving terminal, an amplifier and a variable attenuator were inserted into the connection between the terminals of the equaliser. The levels of the pilot tones at the outputs of the selecting filters were recorded at a number of settings of the attenuator, and the results of this test are shown in Fig. 9.

The overall amplitude/frequency response of the equaliser was obtained by feeding a slowly-sweeping audio tone into the system, and plotting the output level on a pen-recorder. A number of different conditions were tried including operation with spectrum-distorting networks connected between the terminals. The spectrum-distorting networks consisted of audio delay lines connected together to give cancellation of the signal at certain points in the spectrum. For comparative measurements, the action of the equaliser could be suppressed by substituting a special dummy unit for the pilot-tone detectors. This device provided fixed d.c. levels corresponding to the unity gain condition for the gain-controlled amplifiers.

3.2. Subjective tests

Listening tests were conducted on the equaliser, using a panel of seven technical staff. The arrangement of Fig. 10 was employed with limiting and 16 dB compression of the programme material to reproduce the normal pro-

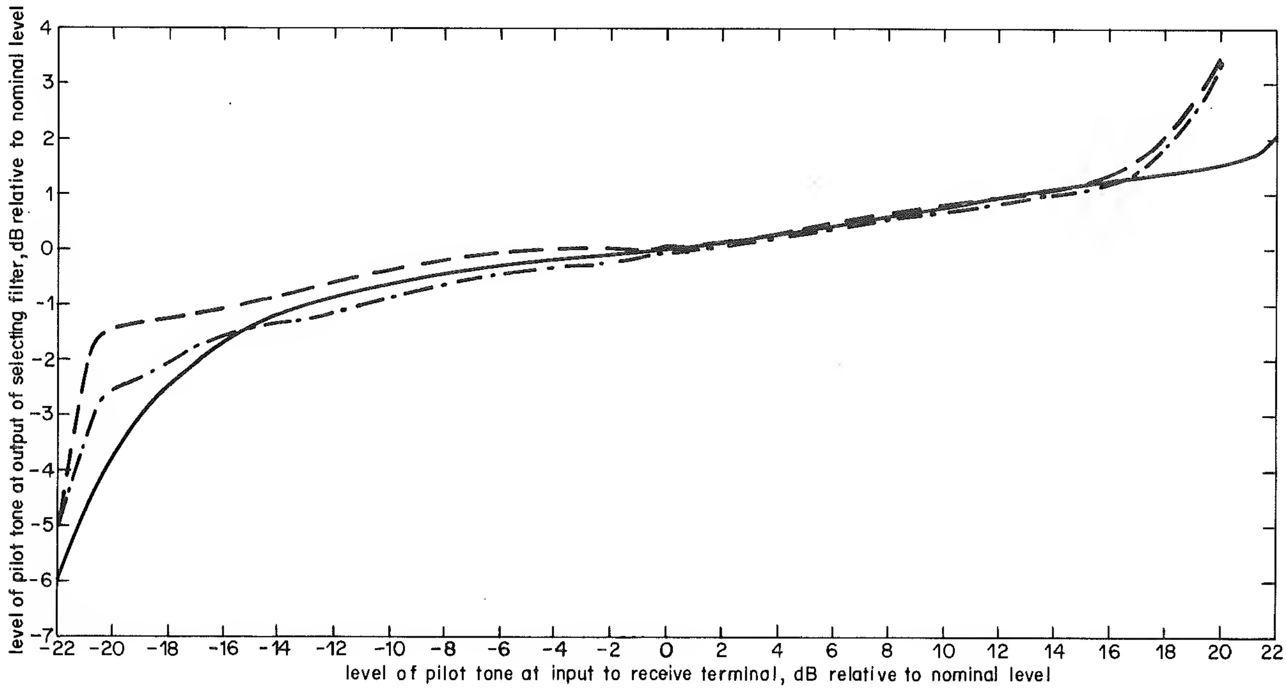

Fig. 9 - Variation of corrected pilot tone level with input pilot tone level

1·185 kHz pilot tone — 2·370 kHz pilot tone — 3·800 kHz pilot tone

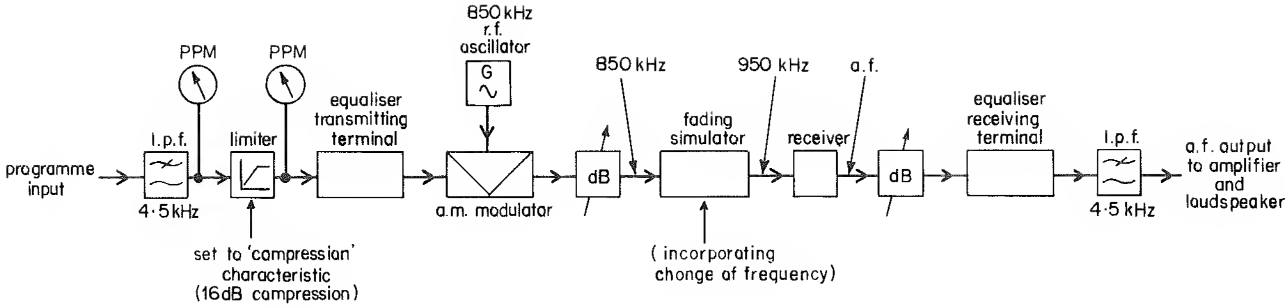

Fig. 10 - Experimental arrangement for subjective tests

gramme characteristics experienced on overseas links. It was not possible to use a high-grade communication receiver for the link as none was available having sufficient bandwidth for the programme, so a domestic broadcast receiver was used after modification to achieve a bandwidth of ±6 kHz. Single-sideband modulation was used for the tests, as the equaliser was intended primarily for use with s.s.b. Sufficient carrier was added to the s.s.b. signal to enable the envelope detector in the receiver to demodulate the signal with a reasonably low level of distortion.

The receiving terminal of the equaliser was equipped with the means to switch the controlled amplifiers to a fixed gain, using the dummy chassis mentioned in the previous section. Listeners were permitted to switch between the automatic equaliser and fixed gain conditions and record their preference according to a seven-point scale.* This system of switching allows the pilot tones to be left on the signal so that the listener's choice would not be influenced by the appearance and disappearance of the pilot tones. Total effective suppression of the pilot tones would have been impractical for these tests, but suppression to 45 dB below peak programme level was achieved and considered acceptable. The programme spectrum was restricted to a bandwidth of 4·5 kHz by low-pass filters as this was found to reduce considerably the annoyance experienced from the residual pilot tones (presumably because some intermodulation was taking place and giving rise to audible products above 4·5 kHz).

The r.f. fading simulator[4] was set up to give deep fades at intervals of approximately eight seconds. An r.f. delay path is incorporated to simulate the path difference between waves received over different ionospheric routes. Each listener participated in two tests; one with a delay path of 250 microseconds and the other with a delay path of two milliseconds. Histograms of the test results are shown in Figs. 11 and 12.

* The points correspond to the 7 grades of the comparison scale given in the CCIR Report 405-1, New Delhi 1970:

+3 A much better than B
+2 A better than B
+1 A slightly better than B
0 A same as B
−1 A slightly worse than B
−2 A worse than B
−3 A much worse than B

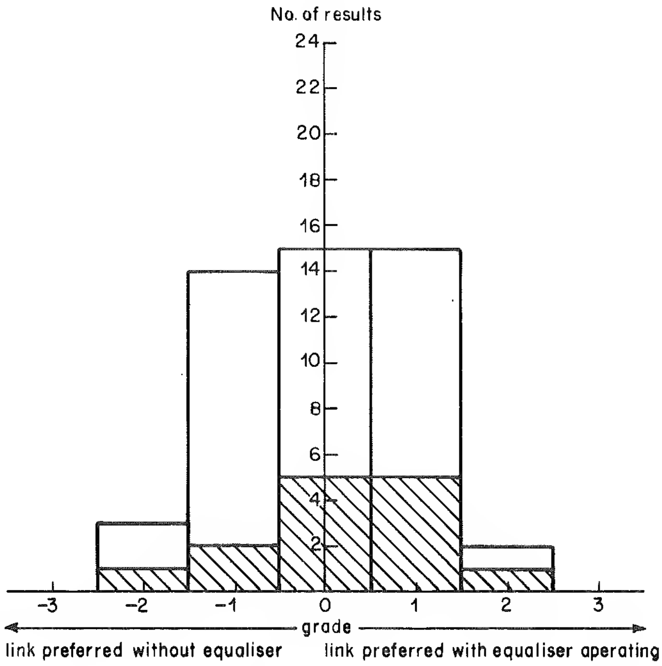

Fig. 11 - Results for subjective tests of automatic equaliser
Delay path in fading simulator 250 μs
Overall result   Result for speech programme alone

The programme material consisted of five music passages and two passages of speech. Results for speech only are shown shaded in the figures, in addition to the overall results.

4. Discussion of results

The objective tests carried out on the automatic equaliser showed that the equipment was capable of restoring a pilot tone to within ±2 dB of the specified level during fading which caused variations of up to ±17 dB in the level at the output of the link. Tests with audio delay networks inserted between the terminals to produce nulls in the spectrum were less encouraging, as the equaliser depends on a single pilot tone to supply the information necessary for gain adjustment in each band. When the pilot tone is suppressed by a deep fade which affects only a very narrow part of the spectrum, the resultant gain adjustment of the

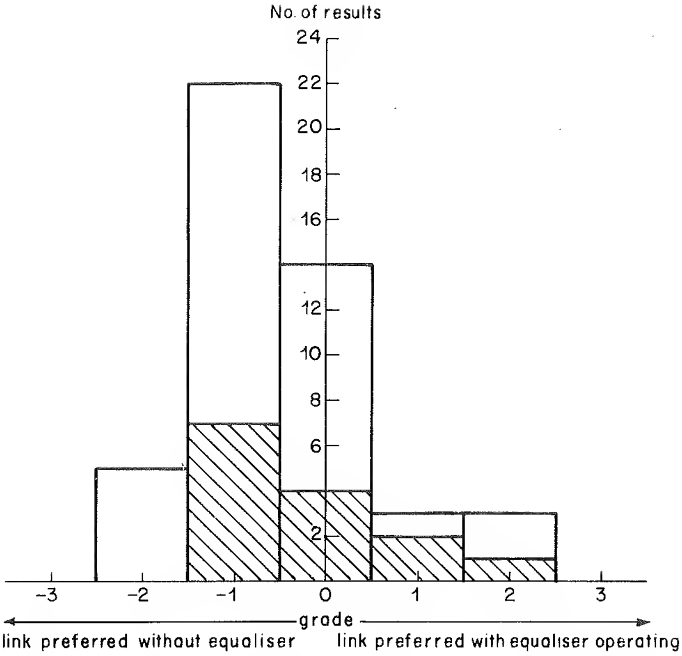

Fig. 12 - Results for subjective tests of automatic equaliser
Delay path in fading simulator 2 ms
Overall result
Result for speech programme alone

appropriate controlled amplifier tends to introduce further distortion by over-correcting in other parts of the spectrum, instead of mitigating the effects of the fading. Despite this observation, it was decided to proceed with subjective tests, as it was possible that this anomalous operation of the equaliser would be a relatively rare occurrence with a constantly-changing pattern of fading (such as that produced by the fading simulator).

The results of the subjective tests given in Figs. 11 and 12 show that, for both speech and music programmes, there is little to choose between the normal and equalised link conditions when there is only a short (250 microseconds) path difference between received waves. There was a slight preference among listeners for equaliser operation on speech, but the overall opinion was that the equaliser neither improved nor degraded the signal. When the 2 ms path difference was simulated, however, the listeners found the effect of the equaliser disagreeable, as indicated by the peak at −1 on the histogram of Fig. 12, both for speech and the overall result.

Two waves arriving at the link receiver with a path difference of 2 milliseconds create minima in the spectrum at intervals of 500 Hz. It is clear that the simple equaliser which employs relatively broad controlled frequency bands (typically 1·2 kHz wide) cannot correct a fading pattern with minima occurring 500 Hz apart, so it is not particularly surprising that the results of Fig. 12 are disappointing. The results for the shorter (250 μs) delay (Fig. 11) show that the equaliser performs more favourably, as might be expected, when the minima are spaced at 4 kHz intervals. Even these results are disappointing, and the reason is thought to be the anomalous operation described earlier.

5. Conclusions

For a simple equaliser of the type constructed, it appears that a single pilot tone at the centre of each controlled band of frequencies in the programme spectrum is inadequate. Furthermore, it became apparent during the work that a larger number of controlled bands would be necessary if differential delays of up to 2 ms between waves incident on the receiver aerial were to be effectively corrected.

Thus the problem of designing an automatic equaliser to work on the pilot-tone principle seems largely a matter of selecting a suitable number of controllable bands together with a sufficient number of pilot tones. If for each of the controlled bands the amplitude of two or possibly three pilot tones could be averaged before the control voltage is derived, then even the total loss of one tone would not have a catastrophic effect on the control signal when a deep fade is encountered.

Adjacent bands could perhaps share the same pilot tone at their common boundary, so that the total number of pilot tones is n + 1 or 2n + 1 according to whether two or three tones are used to control each of n frequency bands in the spectrum. Eleven bands would be necessary to equalise the audio spectrum up to 5·5 kHz satisfactorily when propagation time differences of up to 2 ms are experienced; the proposal would thus entail the use of 12 or 23 pilot tones.

An equaliser on this scale would be a possibility, but rather greater complexity would be required in the filters which define the controlled bands. The overall size of the equipment would also be increased, but perhaps the greatest problem would be the placing of the pilot tones and their associated suppression notch filters in the programme spectrum. Tests with the three pilot-tone notch filters available indicated that their inclusion in the programme chain produced no audible effect. It seems likely, however, that twenty additional notches inserted into the programme spectrum would have a noticeable effect.[5]

The inference drawn from the study of the prototype equipment is that a high degree of complexity would be required, and a considerable modification of the programme spectrum would have to be tolerated. One should not, therefore, rule out the possibility of alternative types of equaliser (for example the type proposed by Rudin[6]) for application to h.f. links. The present work at least indicates that a very simple form of equaliser does not give a worthwhile improvement.

6. References

1. KIFT, F. 1959. The propagation of high-frequency radio waves to long distances. *Proc. Instn. elect. Engrs.*, 1960, **107B**, 32, pp. 127 – 140.

2. KALIYUGAVARDAN, S. 1971. Variable null in RC networks controlled by two elements. *Electron. Engng*, 1971, **43**, 518, pp. 29 – 32.

3. DELL'ORO, E. 1961. Transistorized selective amplifiers using RC networks. *Electron. Engng*, 1961, **33**, 405, pp. 734 – 736.

4. A simulator of ionospheric propagation of amplitude modulated signals. BBC Research Department Report No. 1969/24.

5. Simultaneous subliminal signalling in conventional sound circuits: a feasibility study. BBC Research Department Report No. 1971/1.

6. RUDIN, H.R. 1968. A continuously adaptive equalizer for general-purpose communication channels. *Bell Syst. tech. J.*, 1969, **43**, 6, pp. 1865 – 1884.

SMW/EP/JS

Printed by BBC Research Department, Kingswood Warren, Tadworth, Surrey